INJECTION MOLDING

Injection molding is an important processing technique for converting thermoplastic and thermosetting materials into final products (1–5). In 1985, approximately 3.4×10^6 t (19½%) of the 17.2×10^6 t of thermoplastics sold in the United States were injection-molded.

In the United States, ca 60,000 injection-molding (IM) machines are used in about 6000 plants. They tend to cluster in groups of multiples of twelve, which is all a foreman and crew can handle efficiently. About 95% of the machines are reciprocating or two-stage screws; the remainder are plunger machines. In 1985, 43% of the IM machines were imported.

Injection molding produces parts in large volume at high production rates. Labor costs per unit are low and the process can be automated. The parts require little or no finishing and many different surface finishes and colors are available. The same article can be molded into different materials on the same equipment. Close tolerances can be maintained. Parts can be molded in a combination of plastic and fillers, eg, glass, asbestos, talc, and carbon; metallic and nonmetallic pieces can be inserted.

The process permits the manufacture of very small parts which are almost impossible to fabricate in quantity by other methods. Scrap losses are minimal, as runners, gates, and rejects can be reground and reused. Aside from die casting, it is the only commercial process where the scrap can be reused immediately by regrinding and remolding at the machine. Since energy costs are low, this process is the most economical way to fabricate many shapes.

The profit margins of the plastics industry, however, are very low. Molds, machinery, and auxiliary equipment are expensive and three-shift operations are often necessary to compete. Process control may be poor and machinery may not be consistent during operation. Plastics vary from batch to batch. In addition, viscosity, temperature, and pressure in the mold are continually changing and cannot be measured. Quality is often difficult to determine immediately and the long-term properties of the material are difficult to ascertain. Experience and good workmanship are essential.

Injection-molding Machines

A reciprocating-screw injection-molding machine with a clamping capacity of 300 t and a 6.35-cm (2½-in.) reciprocating screw delivers a maximum of ~570 g (20 oz) of polystyrene per shot (see Fig. 1). The machine clamps the mold halves together, raises the temperature of the plastic to a point where it flows under pressure, injects the hot plastic into the mold, cools the plastic in the mold, opens the mold and ejects the hardened plastic piece.

The injection-molding machine performs these functions automatically under controllable temperature, time, speed, and pressure. Molecular structure, molecular weight, and molecular-weight distribution (all of which control melt viscosity), orientation of the polymer molecules, and crystallizability play important roles in the process and must be considered for their effect on product properties.

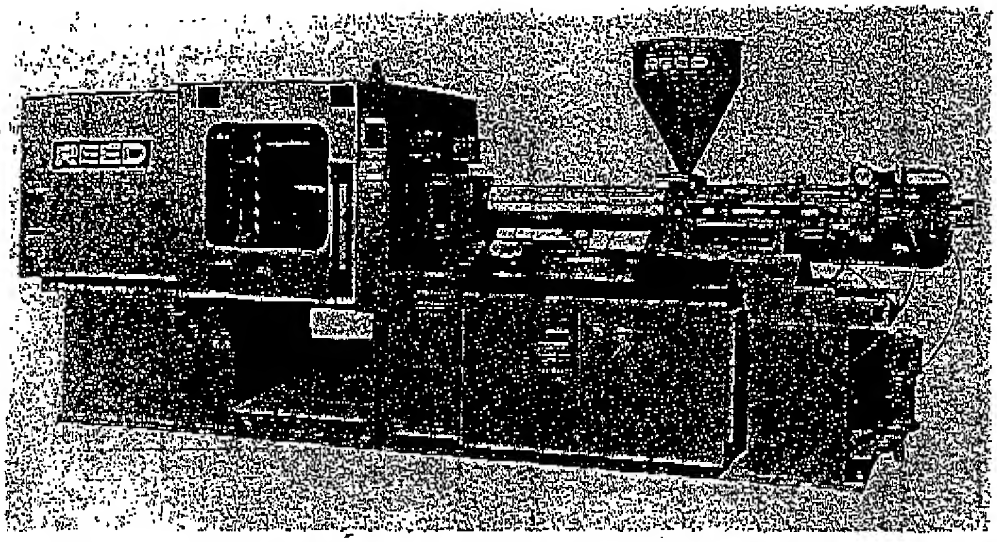


Fig. 1. A 300-t injection-molding machine with a 6.35-cm (2½-in.) reciprocating screw. Courtesy of Reed-Prentice Division, Package Machinery Company.

Injection molding is not a new process. In 1872, a patent was issued for an injection-molding machine for camphor-plasticized cellulose nitrate (celluloid), and a few years later the first multicavity mold was introduced. In 1909, Baekeland discovered phenol–formaldehyde resins, which can now be injection-molded with reciprocating screw-molding machines.

The experimental and theoretical works of Carothers led to a general theory of condensation polymerization that provided the impetus for the production of many polymers, including nylon. At the end of the 1930s great improvements in materials permitted injection molding to become economically viable.

The injection end of the first commercial injection-molding machine was a plunger. It consists of a very heavy steel tube with a nozzle threaded into one end. The outside of the nozzle has a radius which fits into the reverse radius of the sprue bushing of the mold. The melted plastic material is forced into a small hole (3–9.5 mm) (⅛–⅜ in.) by the plunger.

The inside of the tube is taken up by a steel spreader or torpedo which distributes the material around the inside wall. The tube, called a heating cylinder, is heated by electrical resistance heaters (heating bands) and controlled by thermocouples attached to pyrometers. The plunger is a round steel bar that pushes the cold material from the open end of the cylinder toward the hot nozzle end. It is volumetrically fed through a hole in the top rear of the cylinder.

In plunger machines, both melting and injection take place in the same location, although each has different and opposing mechanical requirements. The first revolution in machine design separated the two functions by using two cylinders. The first cylinder, used for melting, is mounted at 45 or 90° to the second or shooting cylinder or pot. The pot is a small-bore plunger cylinder without the torpedo. The two cylinders are connected by a valve. When the valve is open, the melting or plasticizing cylinder pushes the material into the nozzle end of the pot, forcing the plunger back. When the plunger moves back an ex-

perimentally predetermined distance, filling stops and the valve closes because the return motion of the plunger contacts a limit switch. At the appropriate time in the cycle, the material is injected into the mold from the second cylinder, the so-called pot. This operation improves the mixing of the plastics, equalizes the temperature, and gives better control of speed, pressure, and material.

This type of machine is called a preplasticizing machine. Of the equipment in use today, 95% is preplasticizing, either with a reciprocating screw (Fig. 2) or a screw-pot (Fig. 3). In a reciprocating screw, the melted material is collected in

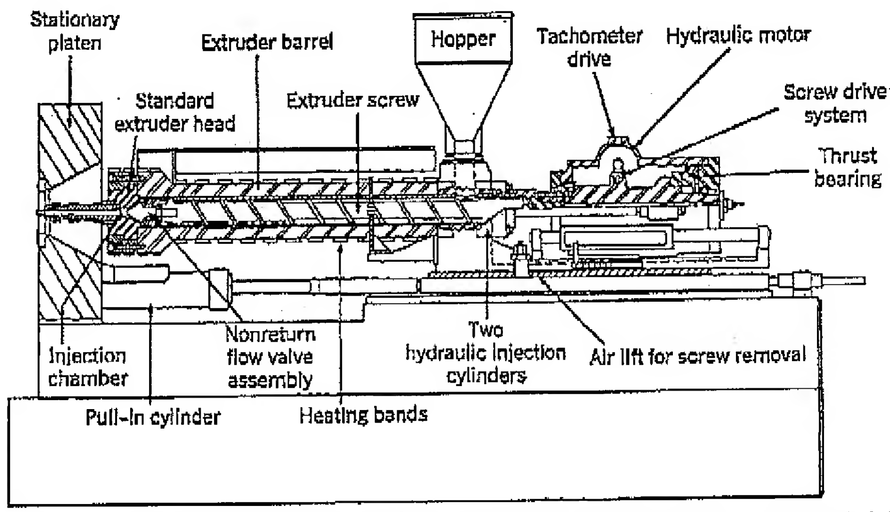


Fig. 2. Reciprocating-screw machine, injection end. Courtesy of HPM Division of Koehring Company.

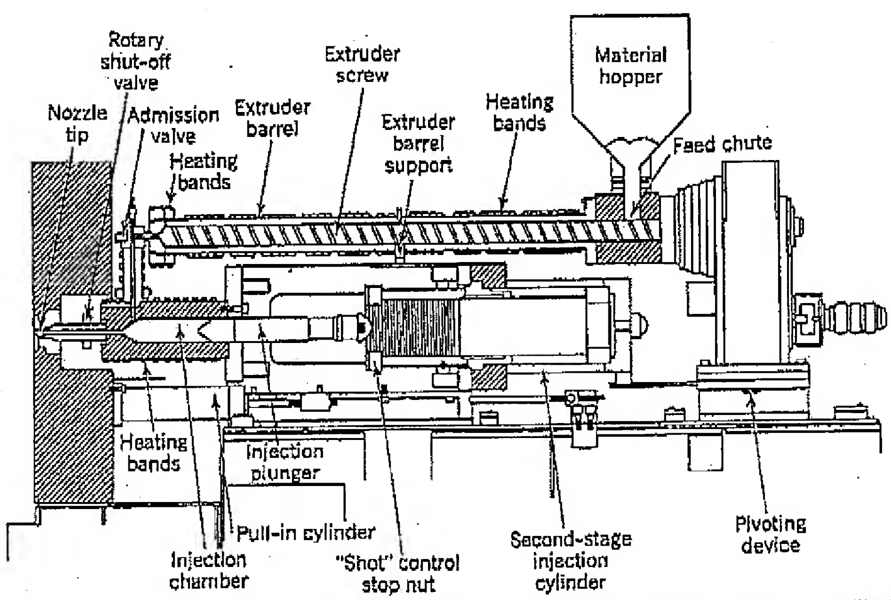


Fig. 3. Two-stage screw-plunger machine. Courtesy of HPM Division of Koehring Company.

front of the screw which continues to move backward as more and more material is melted. The area where the melted material is collected corresponds to the pot in a two-stage machine. A check valve (nonreturn valve) is closed when the screw is pushed forward by the injection cylinders. At this time, the screw and nonreturn valve act like a plunger.

The plunger machine heats the material by conduction. Since plastic is an insulator, the material next to the outside wall is much hotter than that near the center. The laminar flow in the plunger-type cylinder does not reduce the temperature differential. This produces residual stresses in the molded parts which can be very troublesome. The plunger machine is used now only for producing special effects, eg, for mottling; the two-stage plunger is also obsolete.

The second revolution in machine design was the reciprocating screw where the material is melted by the heat generated internally by the friction of molecules rubbing over each other throughout the plastic. The screw is an excellent mixer and quickly replaced the plunger machine.

The last significant change in machine design is the computer-controlled machine with feedback which further improves operation, productivity, and product quality.

Hydraulic molding-machine circuits have not changed in the last 50 years. For a description of hydraulic components, circuits, and nonsolid-state electrical circuits, see Ref. 1.

Solid-state controls and computers have caused radical changes in the electrical systems and circuits (1). Such information is best found in the manufacturer's manuals.

Reciprocating-Screw Injection-Molding Machines. A hydraulic clamping system is shown in Figure 4. In order to minimize cost and power consumption, small-diameter cylinders (not shown) move the large clamp rapidly, using a prefill valve and gravity to force oil behind the large clamp ram. The injection end of an in-line reciprocating-screw plasticizing unit is shown in Figure 2. The ejection side of the mold is clamped to the moving platen. The cavity side is clamped to the stationary platen. The empty space of the mold is filled with melted plastic under high pressure.

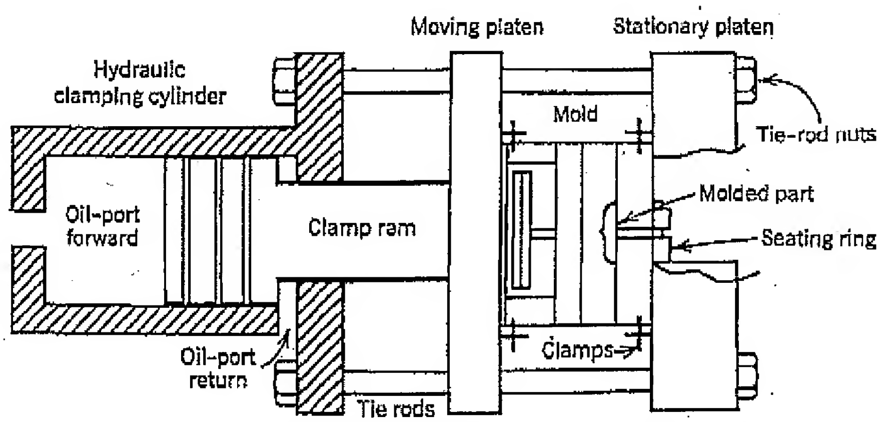


Fig. 4. Hydraulic clamping system. Time, temperature, and pressure controls are not shown.

The moving platen rides on four steel bars called tie rods or tie bars. The clamping force is generated by the hydraulic mechanism pushing against the moving platen and stretching the tie rods.

The molding process for reciprocating screw machines with hydraulic clamps includes the following steps:

1. Granulated plastic material is put into the hopper.
2. Oil is sent behind the clamp ram which moves the moving platen, closing the mold. The pressure behind the clamp ram builds up, developing enough force to keep the mold closed during the injection cycle. If the force of the plastic material is greater than the clamp force, the mold opens, an unacceptable condition causing plastic to flow past the parting line on the surface of the mold producing flash, which must be removed or the piece rejected and reground.
3. The two hydraulic injection cylinders, one on each side of the screw, bring the screw forward, injecting previously melted material into the mold cavity. The injection pressure is maintained for a predetermined length of time. A valve at the tip of the screw prevents material from leaking into the screw flights during injection. It opens when the screw is turning and melting material, permitting the plastic to flow in front of it to force the screw back.
4. The oil velocity and pressure in the two injection cylinders are high enough to fill the mold as quickly as needed and maintain sufficient pressure to mold a part free from marks, welds, and other defects.
5. As the material cools, it becomes more viscous and solidifies to the point where injection pressure is no longer needed.
6. The material is melted primarily by the turning of the screw which converts mechanical energy into heat. It also absorbs heat from the heating bands on the plasticizing cylinder (extruder barrel). As the material melts, it moves forward along the screw flights to the front end of the screw. The pressure generated by the screw on the material forces the screw, screw drive system, and the hydraulic motor back, leaving a reservoir of plasticized material in front of the screw. The screw continues to turn until the rearward motion of the injection assembly touches a limit switch stopping the rotation. This limit switch is adjustable, and its location determines the amount of material that remains in front of the screw (the size of the shot).

   The pumping action of the screw also forces the hydraulic injection cylinders (one on each side of the screw) back. This return flow of oil from the hydraulic cylinder is called the back pressure; it can be adjusted to ca 2.75 MPa (400 psi).
7. Most machines retract the screw slightly at this point to decompress the material to prevent drooling out of the nozzle. This is called the suck back; it is usually controlled by a timer.
8. Heat is continually removed from the mold by circulating a cooling medium (usually water) through drilled holes. The amount of time needed for the part to solidify is controlled by the clamp timer. When the time expires, the movable platen returns to its original position, opening the mold.
9. An ejection mechanism separates the molded plastic part from the mold and the machine is ready for the next cycle.

In Figure 5, the back safety gate is removed showing the operator lifting molded parts from a molding machine; the four tie bars upon which the movable

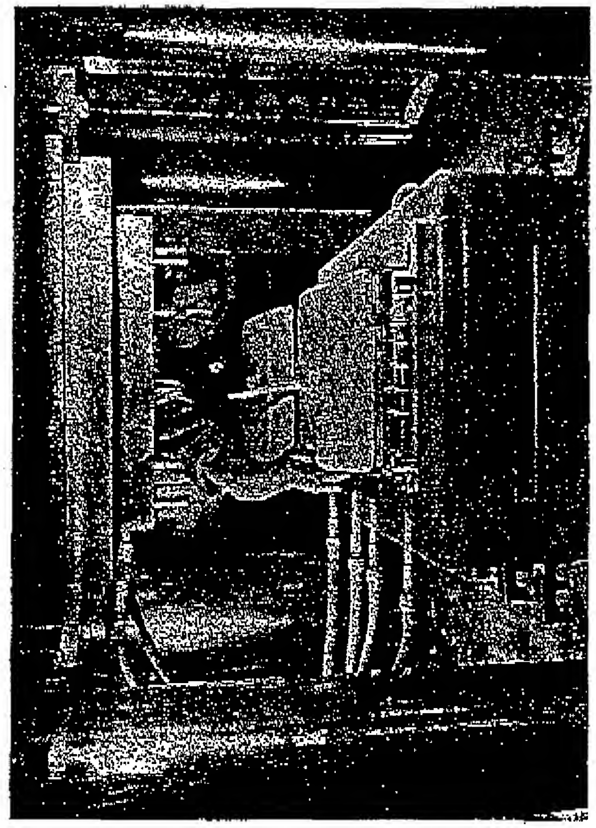


Fig. 5. Operator removing a molded part.

platen rides are visible. The rubber hoses circulate fluid for temperature control. The temperature for each cavity and core can be controlled separately. The mold is held on the platen by clamps.

A cutaway view of a 6.35-cm, 300-ton reciprocating-screw machine is shown in Figure 6. The injection end is always to the right of the operator. This permits him to open the safety gate with his left hand and remove the molded piece with his right hand.

Controls. The location of the hydraulic and electrical controls vary widely and are obviously remote from the valves and solenoids. Some controls are mounted in separate units away from the machine. The controls can be as simple as buttons and dials on timers or interfacing with a computer.

The oil reservoirs are mounted on the floor or above the machines. Pressure may be read from gauges located anywhere or from digital readouts on a panel. The hydraulic system generates a significant amount of heat which is removed by a water-cooled heat exchanger. Water is also used for cooling molds.

The hydraulic and electrical systems should be designed for easy maintenance. Clearly written, well-illustrated instruction manuals are needed. In purchasing a new machine, the instruction manual and quality of repair support should be a factor in selection.

Knockout Systems. Mechanical or hydraulic-pneumatic knockout (KO) systems installed behind the moving platen are used in conjunction with holes

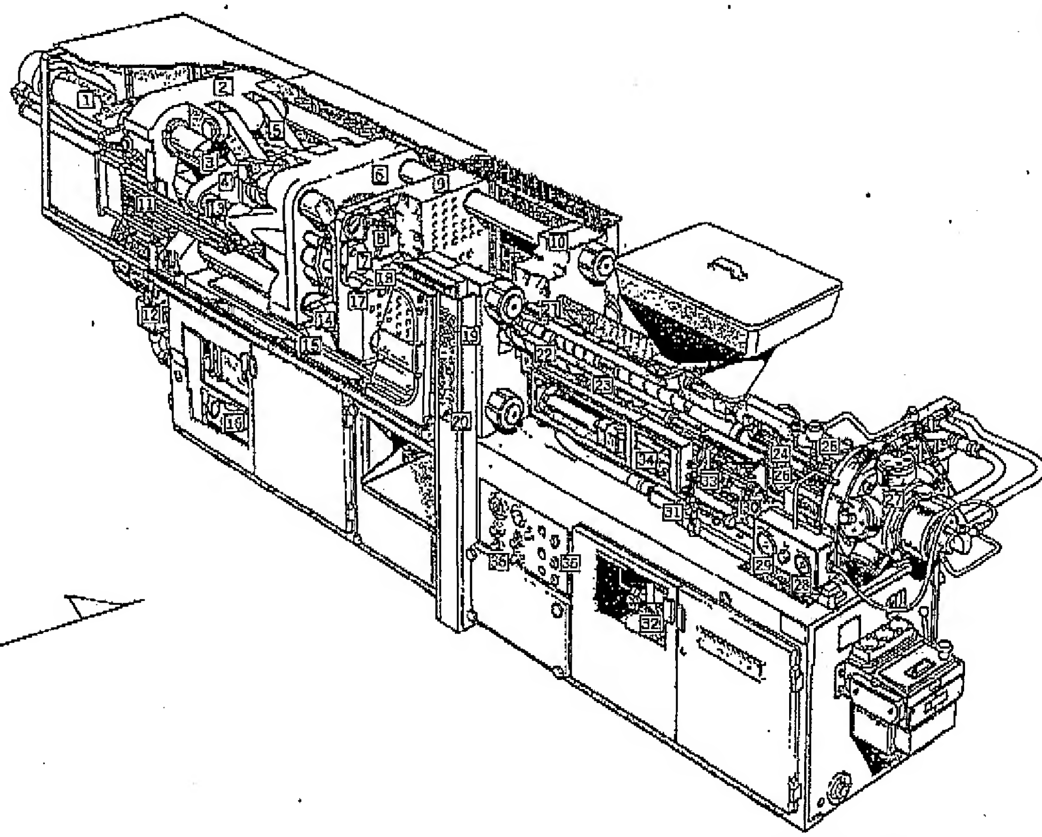


Fig. 6. Cutaway view of a 300-t, 6.35-cm (2½-in.) reciprocating-screw machine (Peco molding machine). (1) hydraulic cylinder; (2) tail stock plate; (3) hydraulic piston extension; (4) toggle crosshead; (5) toggle link; (6) moving back plate; (7) ejector plate; (8) mold height-adjustment screw; (9) moving platen; (10) stationary platen; (11) limit switches and stops; (12) lubrication pump; (13) toggle crosshead guide bar; (14) mold height-adjustment mechanism; (15) moving-plate support pad; (16) hydraulic tank; (17) ejector bar; (18) hydraulic ejector; (19) solenoid indicator lights; (20) manual-control panel; (21) injection heating cylinder; (22) screw; (23) air tube and bore; (24) screw coupling; (25) bearing; (26) hydraulic-motor drive shaft; (27) hydraulic motor; (28) screw-speed indicator; (29) injection pressure gauge; (30) shot-volume control mechanism; (31) retraction stroke-limit switch; (32) screw-speed control; (33) injection secondary-pressure control; (34) hydraulic injection cylinder; (35) water valves; and (36) hydraulic controls.

in the moving platen whose location and size have been standardized by the Society of the Plastics Industry (SPI).

In the mechanical system, a stationary KO plate is placed on the machine to which bars are attached that pass through the platen and the back plate of the moveable half of the mold. Pins or other devices are attached to the KO plate of the mold. The other end of the pin or device is in the molding area. After the part is molded, plastic is in direct contact with the top of the KO pins or devices. As the mold opens, the KO plate of the mold hits the bars that are attached to the stationary KO plate of the machine. This stops the motion of the mold KO plate. The rest of the mold continues to move back, leaving the molded part on the front end of the KO pins, thus ejecting the pieces.

There are four push-back pins attached to the four corners of the mold KO plate which also move forward. When the mold closes these pins contact the other side of the mold before the KO pins and force the mold KO plate back to its original position without damaging the tips of the KO pins. In mechanical systems, the operation is machine dependent and the KO system only works when the machine is opened. To return the mold KO plate to its molding position, the machine has to be moved forward until the KO bars are below the top surface of the mold backup plate; this is a cumbersome operation.

A superior and more expensive method uses two hydraulic or pneumatic cylinders to activate the machine KO plate. It can be moved backward and forward (bumping) at various speeds and force as often as desired. It can be retracted or extended at any time in the cycle.

Clamping Systems. The machine is clamped by a hydraulically operated toggle system or a fully hydraulic one. In both instances, a hydraulic cylinder provides the force to stretch the tie bars which cause the clamping action. In a straight hydraulic system, a large-diameter hydraulic cylinder is attached directly to the moveable platen. The clamping force is rated in tons; it should not be confused with pressure. Force and pressure are related: force = pressure × area.

For example, if a press with a hydraulic clamp has a 50-cm (20-in.) diameter clamping cylinder and the maximum working line pressure is 13.8 MN/m^2 (2000 psi), the clamping force is 2.7 MN (314 short tons). The press would be called a 300-ton (short-ton) press.

Clamping force is one of the main machine specifications. Machines available today range from 5.5-ton machines, whose maximum shot is 10 g (⅓ oz), to 5500-ton machines that can mold 25 kg (54 lb) polystyrene per shot. Clamping forces in this section are given in short-ton units specified by machine manufacturers. A 1-ton clamping force corresponds to ~9kN.

Hydraulic clamping permits unlimited pressure selection that can be continually monitored with a pressure gauge (6). As molds get bigger, longer strokes are required for the movable platen. In addition, larger molds require larger clamp forces and larger-diameter cylinders. Cylinders of such size are very expensive. Using a much smaller-diameter cylinder for rapid movement and a large-diameter cylinder for generating the clamp force reduces costs.

Toggles are available in many different systems (7). Basically the hydraulic cylinder [Fig. 6 (1)] is attached to a stationary plate [Fig. 6 (2)]. It moves forward, eventually spreading the toggle links [Fig. 6 (5)] into a straight line and holds them there. The mechanical advantage is between ca 20:1 to 30:1. The toggle system is less expensive to build than the hydraulic system. It requires good maintenance because wear reduces the clamping tonnage. Pressure adjustment is not as easily or accurately controllable as with a hydraulic system.

A clamping force is required to keep the mold closed and to overcome the opening force generated by the injection of the plastic material. The strength of clamp force depends on the projected area of all the molding (parts and runner). The projected area is most conveniently estimated by imagining you are looking from the heating cylinder to the clamping end. If the mold is transparent and everything molded is black, ie, parts and runner, the visible area of the black would be the projected area. In other words, if a part is molded behind another

part, it would not be visible, and therefore would not be included in the projected area.

For design purposes, a good approximation is 0.4 tons of clamp force for each square centimeter (2.5 tons/in.^{2}) of projected area. Hence, for a projected area of 625 cm^2 (100 in.^{2}), a machine with a minimum clamp force of ca 250 tons would be selected.

The clamp stroke is the maximum distance the clamp can move. Maximum daylight is admitted at the farthest distance the platens can separate from each other. The difference is the minimum die thickness that can be put into the press while still maintaining clamping pressure. This minimum distance can always be reduced by adding a bolster plate in front of or behind the movable platen. These are important specifications, indicating how deep a piece may be molded and whether a mold of given depth will fit in the machine.

The clearance between the tie rods determines whether a mold of a given length or width fits. For example, a press has a 50-cm (20-in.) clearance vertically and 45-cm (18-in.) clearance horizontally. Therefore a mold less than 50 cm wide but over 50 cm long fits vertically; a mold less than 45 cm high but over 45 cm long fits horizontally. The length and width dimensions of a mold are often determined by the side parallel to the knockout plate. Molds often extend beyond the tie bars, and with proper design beyond the platen.

Injection End. The injection end has a hopper for holding the material. Hygroscopic materials, eg, nylons, polycarbonates, acrylics, acrylonitriles, and acetates, require drying (qv) before molding.

There are three methods for drying plastics. A hopper dryer, placed on top of the feed mechanism, circulates hot, dry air (dehumidified in some instances) through the material. In the second method, the material is predried in shallow trays in an oven by hot, dry, dehumidified air. The third method uses a vented screw, which melts the material and decompresses it to atmospheric pressure, permitting the water and other volatiles to escape through an opening in the cylinder. The material is recompressed as it moves beyond the vent toward the nozzle and is injected in the usual way into the mold.

A magnet is placed in the hopper throat to catch any magnetic material accidentally introduced into the hopper or material.

Injection Screw. A typical injection screw is shown in Figure 7. It is, in effect, a series of endless buckets, ie, a mechanical conveyor (see SCREW DESIGN;

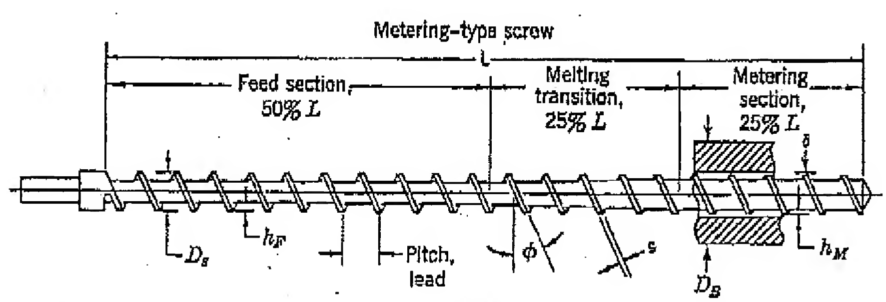


Fig. 7. Injection screw. D_B, diameter barrel; D_S, diameter screw (nominal); ϕ, helix angle (one turn per screw diameter, 17.8°); s, land width; h_F, flight depth (feed); h_M, flight depth (metering); L, overall length; δ, flight clearance (radial); L/D, ratio of length to dia; and h_F/h_M, compression ratio.

EXTRUSION). The volumetric output equations of a screw are essentially a mathematical description of the screw's volume multiplied by its speed, less the plastics resistance to flow.

The material melts by molecular shearing. The resultant friction generates heat. Part of the polymer molecule adheres to the barrel wall or the screw and causes motion toward the nozzle end. Thus, heat is generated directly into the material.

Heating bands are used to compensate for the black-body radiation of the cylinder; otherwise it would be necessary to overheat the plastic and to adjust the final temperature. About 70% of the energy input of the cylinder is used toward turning the screw (melting material); about 27% is consumed by black-body radiation losses and 3% by adjustment of the final temperature.

The injection screw is divided into three parts. The first half compresses the material and removes the air; the flight depth (h_F) is constant. The second part (third quarter) has decreasing flight depths, reducing the volume. Reduction of volume increases friction and heat in the melting section. At the end of the third quarter, all the material should be melted (plasticized). The last section is a pump. The flight depth (h_M) is constant but smaller than in the first section because the volume of the melted material is reduced. Calculations about screw output relate only to this section.

On all injection screws, one thread per screw diameter is standard. Thus the *ratio of length to diameter (L/D) indicates* the number of *turns (flights)*. The reciprocating screw continually moves rearward under the hopper as it operates, reducing the number of available flights. An L/D of 20:1 is highly recommended.

Torque. The work of melting the material is done by rotating a screw in a stationary barrel. The rotational force, called torque, is the product of the tangential force and the distance from the center of the rotating member. Torque is related to the power of an electric motor and depends on the motor's speed. A 22-kW (30-hp) motor has the following torque at various speeds:

Speed, rpm	*Torque, J (ft·lb)*
1800	119 (87½)
1200	180 (133)
900	237 (175)

The speed of a given motor is built into the motor. Speed and torque can be changed by adjusting the output speed of the motor with the help of a gear train. The change in torque varies inversely with the speed.

The a-c motors develop a starting torque of almost twice the running torque. The screw has to be protected against overload to prevent breakage. This problem is not encountered with a hydraulic drive.

The drive must supply enough torque to plasticize at the lowest possible screw speed, but not enough to mechanically shear the screw. Changes in torque are needed because of the different processing characteristics of plastics. Much higher torque is required to plasticize polycarbonate than polystyrene. The speed of the screw regulates the quality and output rate of the polymer. A choice of two, and preferably three, torque-speed ranges is desirable for handling the various materials. If a material is being molded with a minimum torque at a given speed, increasing the speed increases the power requirements.

Control of torque and speed by valve adjustment is very important. The

hydraulic motor has infinitely adjustable constant torque output. Its speed is controlled independently in stepless increments. The system can never develop more than its designed torque and, therefore, screws do not break. A hydraulic drive allows a lower melt pressure since it is much lighter than an equivalent a-c motor and drive. These are some of the reasons why most machines use hydraulic motors.

The strength of the screw limits the input power. As power is increased, a point is reached where the torque that can be provided is above the yield strength of the metal screw. The strength of the screw varies with the cube of the root diameter. For a 6.35-cm (2½-in.) screw at 200 rpm the maximum permissible power is 30 kW (40 hp), and for a 11.4-cm (4½-in.) screw at 150 rpm, it is 134 kW (180 hp). For a given power, the slower the speed, the higher the torque. A high shear rate degrades the material. The shear rate is highest at the barrel wall. The maximum surface speed with present screw technology is ca 45 m/min. Some of the more shear-sensitive materials limit the surface speed to 30 m/min.

Power Requirements. The work performed in screw plastication causes the temperature to rise to the molding temperature. Assuming that all the energy derives from turning the screw and that the mechanical efficiency is 100%, the work would be the product of the average-specific heat and the temperature rise. Neither of these assumptions is correct. A small amount of heat is supplied by the heating bands, and corrections for machine efficiency must be made. Since the screw acts as a pump, energy is also required when pressure is generated. This is relatively small and is disregarded in subsequent calculations. Therefore

$$\text{Power} = C \times (T_p - T_f) \times Q + \Delta P \times Q$$

where C = average specific heat; T_p = temperature-plasticized material; T_f = temperature-feed material; Q = throughput, continuous rotation; and ΔP = back pressure.

For example, high impact polystyrene has an average specific heat of 1.76 J/(g·°C). The power required to plasticize 1 kg/h at 21°C can be calculated to be 0.13 kW (0.17 hp). This is equivalent to 7.7 kg/h for each 1-kW (1.3-hp) input. Molding materials range from 3.5–8.3 kg/h for each 1-kW (1.3-hp) input.

If a 22-kW (30-hp) motor is used at a RT of 27°C, the maximum output of low density polyethylene (C = 3.3 J/g·°C) at 193°C is 101 kg/h.

If the material temperature is raised to 232°C, the output decreases to 82 kg/h. Thus raising the temperature lowers the maximum output, and therefore the operation is performed at the lowest possible melt temperature. This gives maximum screw output and reduces the time needed for cooling the polymer in the mold.

Theoretically the output of the machine as defined in the previous equation is independent of screw diameter. If, for example, 6.35-cm (2½-in.) and 8.89-cm (3½-in.) screws, each having the same L/D ratio and the same input drive power, are operated at their maximum capacity, they both deliver the same output (kg/h). The plastic remains longer in the larger screws. The relationship between power, torque, and speed shows the reason for large screws. Screw speeds must be kept low to prevent degradation. With constant power, the torque developed at slower speeds can be high enough to shear the screw. For a 6.35-cm screw at 200 rpm, the maximum permissable drive input is 30 kW (40 hp). Therefore, the higher power required for higher output needs larger-diameter screws to prevent break-

age. The torque a screw can safely carry is proportional to the cube of its root diameter.

It is obvious that in a screw machine, the power rating available for screw rotation is a very important specification. Assuming similar efficiency for different screw designs, the maximum output, which is a primary concern of injection molders, is largely determined by the power rating of the screw.

Screw Plasticizing. In a screw, the melting of the plastic is caused by the shearing action of the screw, which converts the mechanical energy of the screw drive into heat energy. The heat is applied directly to the material. This and the mixing action of the screw contribute to plasticization which offers the following advantages:

High shearing rates lower the viscosity. The flow is nonlaminar. Good mixing homogenizes the melt. The residence time in the cylinder is approximately three shots compared to 8–10 shots of a plunger machine. Most of the heat is supplied directly into the material; the cycle can be delayed for a longer period before purging. The method can be used with heat-sensitive materials, such as PVC. The action of the screw reduces material holdup and subsequent degradation. The screw is easier to purge and clean than the plunger.

Reciprocating-Screw System. In a reciprocating screw (in-line screw) (Fig. 2), the material is fed from the hopper, plasticized in the screw, and forced past a one-way valve at the injection end of the screw. The material accumulates in front of the screw, forcing back the screw, its drive and motor, and the pistons of the two hydraulic injection cylinders. The return oil from these cylinders passes through the so-called back-pressure control valve into the tank. This valve controls the mixing in the cylinder. The higher the pressure setting, the more complete the mixing.

When the screw reaches a certain position, it contacts a switch which stops the rotation. When the cycle is ready to inject, two hydraulic cylinders, one on each side of the carriage, move the screw assembly forward, and use the screw as an injection ram. The one-way valve prevents the material from passing back over the flights. If this valve does not function correctly, the screw rotates during injection and the shot size cannot be controlled.

Screw-Plunger System. In the screw pot (screw plunger or two-stage screw) shown in Figure 3, a fixed screw is used for plasticizing. A reciprocating screw would permit continual operation of the screw throughout the whole cycle.

The reciprocating screw and screw pot are both preplasticizing systems. They differ in the location of the pot, which is in front of the reciprocating screw and is a separate cylinder in the two-stage machine. Most machines are of the reciprocating type, but screw-pot equipment offers significant advantages:

Because the screw does not act as the injection ram, lighter bearings can be used. There is no need for the heavy-thrust assemblies found on reciprocating screws that reduce maintenance costs.

The extruder barrel need only be strong enough to maintain the pressure of the material during plasticization which is rarely over 34.5 MPa (5000 psi). In contrast, the barrel for the reciprocating screw must maintain the 38 MPa (20,000 psi) applied. There is less wear because the screw does not move.

The connection between the two stages can be a ball check valve, which is troublefree and easy to maintain. It presents minimum flow resistance.

The nonreturn valves at the tip of a reciprocating screw wear rapidly, some-

times do not seat properly (preventing consistent molding), can cause wear in the barrel, retain and degrade material, and are much more expensive than ball check valves.

The small clearances between the plunger and barrel of the second stage help in degassing the material.

The connection between the two stages results in better mixing of the melt.

All the material passes the full flights of the screw, receiving the same amount of heat. In a reciprocating screw, only the first material in passes the full length of the screw.

In a two-stage machine, the screw pumps only against the injection ram, which is floating in oil in the hydraulic cylinder. The reciprocating screw must push back the whole weight of the carriage including the equipment. Therefore, the shot size control is considerably more accurate in the two-stage machine.

Because part of the energy input is used to push the heavy carriage back, an in-line machine gives slightly less output per unit input.

Control of injection speed and pressure is better in screw-pot equipment, and a larger area can be molded. Extremely high injection pressures are available.

The size of a pot in front of a reciprocating screw is limited by the length of the feed section. If the screw moves too far back, the material does not plasticize correctly. In a two-stage machine, there is no limitation; thus a 5-cm (2-in.) reciprocating screw normally has a maximum shooting capacity of 369 g (13 oz), whereas the same-diameter screw can be readily used to shoot 2.8 kg (100 oz) in a two-stage machine.

The two-stage machine, however, requires two cylinders and two sets of heat controls. It is more difficult to clean and to set up, and materials sensitive to high heat cannot be processed. Furthermore, it takes up more space than a reciprocating screw, and it is more expensive. Cylinders for molding thermosets and rubber are designed only for reciprocating screws.

Intrusion Molding. For the molding of heavy sections or when the shooting capacity of the machine is not adequate, intrusion molding is used where the screw turns continuously, filling the cavity directly. When the cavity is filled, a cushion is extruded in front of the plunger, which comes forward to supply the needed injection pressure.

Thermoset Molding. Thermoset material can be molded on reciprocating screw machines. The screw is designed differently and the barrel is usually heated with hot water. The material cannot be permitted to cool in the cylinder. If it does, the screw has to be removed and the thermosetting material must be chipped out.

Specifications. *Injection End.* Injection end specifications vary for different methods, but all include the following: the maximum weight (in ounces) of material that can be injected in one shot is based upon molding general-purpose polystyrene; that is, eg, a 16 oz (453.6 g) machine. A more accurate specification is the volume of material per shot (cm^3). This is a measure of the geometry of the cylinder and feed system. The injection stroke is the maximum distance that the injection plunger can travel. The injection speed (cm/min) is the speed of the injection plunger usually without material in the cylinder. The maximum injection rate is the rate at which the injection cylinder can eject fully plasticized material into air; it differs from the machine speed achieved during molding.

With regard to the amount of pressure that is placed directly upon the

material, an injection pressure of 138 MPa (20,000 psi) is standard. In a two-stage machine or in-line screw, the injection pressure depends upon the diameter of the screw or plunger, the piston diameter of the hydraulic injection cylinder, and the oil pressure. In straight plunger machines, the injection pressure on the material is sometimes given, based upon the same factors. There is, however, at least a 30% pressure loss from the feed end to the nozzle. This loss is related to the granular condition of the cold pellets in the back of the cylinder. Material pressures of 138 MPa (20,000 psi) are required to mold some of the new resins.

The plasticizing capacity is the most important injection-end specification and the most difficult to verify. The Society of the Plastics Industry (SPI) has adopted a specification developed by a technical committee of the Society of Plastics Engineers (SPE).

The rate of recharging (g/s) (oz/s) indicates how much material the screw can produce running continuously. In most machines, the screw runs intermittently and the output is estimated based on the type of molding; a good average approximation is 50%.

Other injection-end specifications include screw speed, diameter, torque, L/D, electrical heating, and hopper capacity.

Clamp End. The clamping end is hydraulic or toggle; its clamping force is rated in tonnage. Other specifications follow.

The horizontal and vertical clearance between the tie bars give the maximum-size mold that fits into the machine in each direction. Molding beyond the tie bars presents no difficulty. The size of the platens is self-explanatory. Molding can extend beyond the platens if the mold is strong enough or properly supported.

The maximum daylight is the maximum distance between the two platens. The stroke is the maximum distance the moveable platen can move. The difference between the two is the minimum mold thickness necessary to obtain full clamping force. From these data combined with the mold configuration and piece part dimensions it can be determined whether the part can be removed from the mold after molding.

The knockout specification indicates whether the system is mechanical, hydraulic, or pneumatic. It gives the stroke of the knockout plate. The Society of the Plastics Industry (SPI) has established a standard knockout-hole pattern followed by all manufacturers.

Speeds for the clamp and injection ends without material are given.

Low pressure closing prevents the full clamp force from building up unless there is no obstruction on the mold surfaces. This is an excellent mold-protection system; it is specified if available.

Other Specifications. Types of control (solid-state, computer, computer-with-feedback), heating-cylinder controls and specifications, number of motors and their sizes, hydraulic-pump capacities, water-cooling requirements, and physical descriptions of the machines are some of the other specifications.

Injection Molds

A high quality mold is absolutely essential for a profitable molding operation. An excellent mold is one that produces the designed part time after time without interruptions or deviation in cycle, with minimum downtime for repair,

and with enough cooling to ensure minimum cycle time for the life of the mold. Customer, designer, molder, quality control, packaging, and moldmaker must agree on the design of the part, its parting line, ejection, surface finish, quality specifications, etc. It is then the responsibility of the molder and moldmaker to build a mold which, in turn, will produce a part fitting these specifications. Ultimately the molder has the responsibility for producing an acceptable part.

The hot plasticized material is injected into the mold where it is maintained under pressure. When the plastic material has sufficiently solidified, the machine opens, the mold halves separate, and the plastic pieces are ejected.

The quality of the part and its cost of manufacture are strongly influenced by mold design, construction, and excellence of workmanship.

The molds become larger and more expensive as machine capacity increases. Costs range from $2,000 to $400,000 for a two-cavity automobile-dashboard mold. This is only a small part of the investment. Development and marketing costs are much higher.

Most critical are the piece-part and mold designs. A failure does not necessarily result in piece-part failure, though it may well do so. It lowers productivity, increases mold maintenance, and reduces part quality.

The first step in mold design is a drawing noting tapers, tolerances, shrinkage and surface-finish specifications, materials, part identifications, and other pertinent information. A model of the part to be molded is desirable. Metal for the cavity and core is selected.

The design includes number of cavities; parting line of the piece, ie, where the faces of the cavities and core touch; gate (entry point of hot plastic into the cavity); gating system which transfers hot plastic into the cavity; runner system which moves hot plastic from the plasticizing chamber to the gate; method of ejection; location of the ejecting devices; temperature-control channels; and venting system, which removes the air that is displaced by the plastic.

Computer-assisted Moldmaking. Computer-assisted design (CAD) and computer-assisted manufacture (CAM) are being rapidly adopted by the American plastics industry. The former is extremely helpful in the design of a part. Views, cross-sections, projections, changes in size and color, and mechanical and thermal analyses are easily made by the computer.

CAD is also extremely useful as a drafting tool and can produce menu-driven drawings very rapidly. Proper programming prevents common errors.

There are a number of software programs that deliver mold designs. However, they are based on many assumptions, some of which are incorrect, so that they should be used with caution by inexperienced molders. The software is of help to very experienced mold designers.

In addition to its other functions, CAD transfers the mold design into metal-cutting instructions. This is common practice in the metal-working industry and is now being applied to moldmaking.

Mold Base. The steel parts that enclose the cavities and cores are called the mold base, mold frame, mold set, die base, die set or shoe (Fig. 8). The sprue bushing is centered by the locating or seating ring on the stationary or injection platen directly in line with the nozzle of the injection cylinder. The sprue has an opening in the center of a concave spherical surface, whose counterpart is an equivalent convex surface on the nozzle of the injection heating cylinder. The

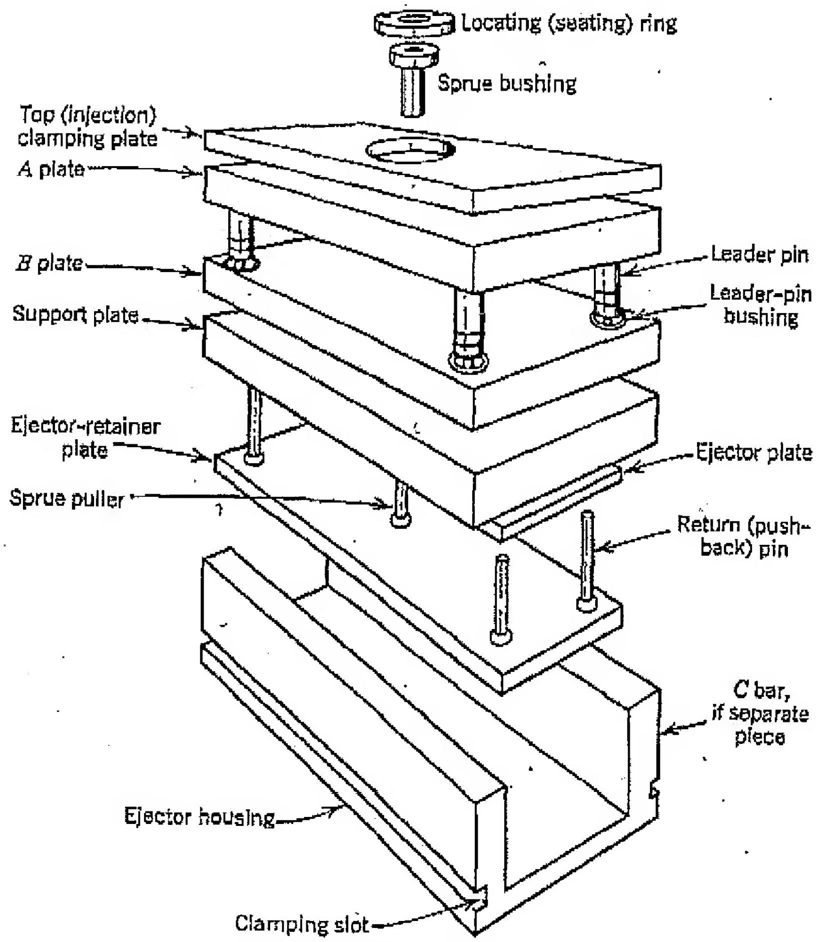


Fig. 8. Standard mold base. Courtesy of D-M-E Corporation.

opening of the sprue bushing must always be larger than the opening in the nozzle in such a way that when the plastic hardens it does not form an obstruction larger than the sprue opening; that would cause the sprue to stick. A generous taper facilitates removal of the plastic. The standard radii for sprue bushings and nozzles are 1.27 (½ in.) and 1.9 (¾ in.) cm, respectively.

The injection or top clamping or backup plate supports the cavity or *A* plate. The cores are attached to the *B* plate, which is supported by its backup plate. The cores on the *B* plate match the cavities in the *A* plate.

Ejector or knockout (KO) pins and other KO devices are mechanically attached to the ejector-plate assembly in such a way that the molded parts can be knocked out and removed from the mold.

A number of companies manufacture standard mold bases and parts. Because of high volume their mold bases are usually less expensive and superior to those manufactured by moldmakers. Replacement parts are standard and readily available at low cost.

Some cavities and cores are of such size or shape that a mold base is best built around them. Several types of steel are available for the mold base. The

best quality is recommended for molds that require high quality parts or a long production run.

Mold Types. The injection mold is identified descriptively by a combination of some of the following terms:

Parting line

regular
irregular
two-plate mold
three-plate mold

Material

steel
stainless steel
prehardened steel
hardened steel
beryllium copper
aluminum
brass
epoxy

Surface

chrome-plated
electroless nickel
etched

Number of cavities, methods of manufacture

machined
hobbed
gravity cast
pressure cast
electroplated
EDM (spark erosion)

Runner system

hot
insulated

Gating

edge
restricted (pin-pointed)
submarine
sprue
ring
diaphragm
tab
flash
fan
multiple

Ejection

stripper ring
stripper plate
unscrewing
cam
removable insert
hydraulic core pull
pneumatic core pull
knockout pins

Two-plate Molds. The cross-section of part of a regular two-plate injection mold is shown in Figure 9. The part being molded is a shallow dish; the cavities are gated on the edge. Temperature-control channels are present in backup plates and in the cores and cavities. Because there is significant insulation between two pieces of metal, channels in cores and cavities give better and more efficient temperature control.

Support pillars are between the back plate and the support plate which is underneath the cores in the *B* plate. A machine knockout bar is shown. These bars remain stationary and as the moving platen returns, they stop the ejector plate. The mold opens on the parting line and an undercut over the sprue puller pulls the molded sprue and runner with it. The part design and mold condition keep the plastic on the core. The ejector pushes the parts off the core and the sprue pillar moves forward, allowing the parts to be removed.

Three-plate Molds. A mold for a deep cup, which can be gated only in the top center section, is constructed as a one-cavity mold feeding directly from the

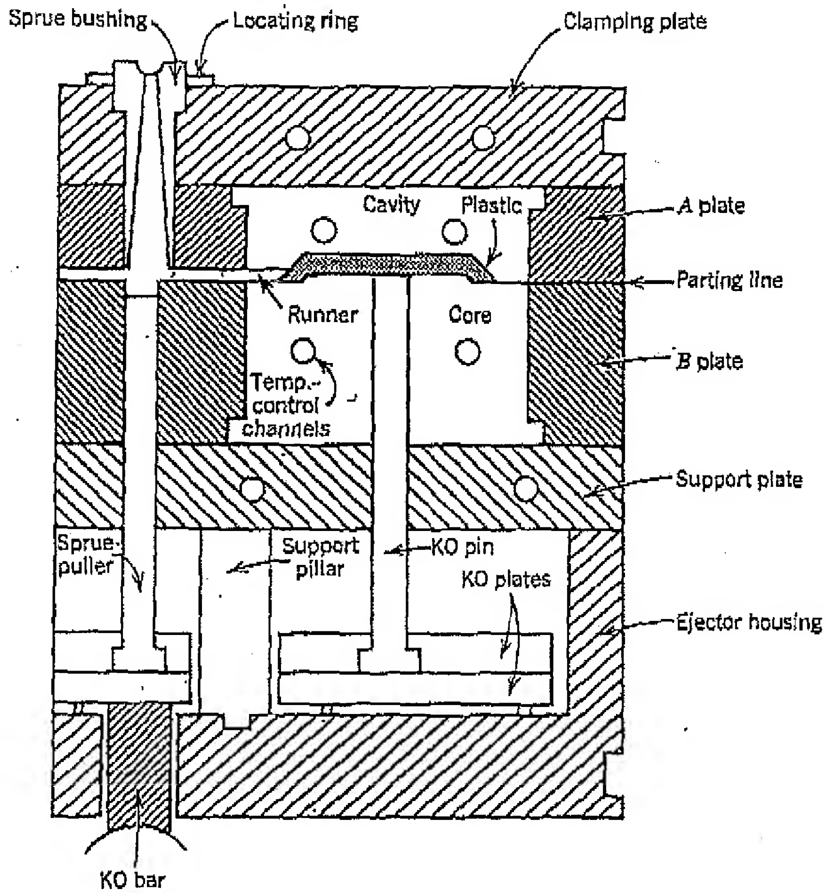


Fig. 9. Two-plate mold. Courtesy of Robinson Plastic Corporation.

sprue. A number of alternatives are available for multiple-cavity molds (see Fig. 10); eight cavities for example could be located in two parallel rows of four. One cavity and core are shown with other significant parts of the mold.

The difference between this type of mold and the two-plate mold shown in Figure 9 is that it separates between the *A* plate and the clamping plate, as well as at the parting line. It is called a three-plate mold because plastic is molded between three plates. The plastic is injected through the sprue bushing into the runner, which is cut into the plate with a trapezoidal cross-section. The flat back is on the pin plate. The plastic flows into the part through an auxiliary sprue bushing, which can be machined directly into the *A* plate and cavity. However, the advantage of a separate bushing is that it can be replaced or changed.

When the mold opens, the *A* and *B* plates move together. Sometimes this happens of its own accord, otherwise latching or spring mechanisms are needed. The mold opens initially on parting line (PL) 1 (Fig. 10). This breaks the gate and leaves the runner attached to the pin plate because of the undercut pins, A, attached to the injection backup plate and extending into the runner. After the separation has occurred at PL 1, the mold continues to open separating at PL 2. The molded pieces are on the core and are ejected in a conventional manner, in this instance by a stripper plate. The pin plate is limited in its travel by stripper

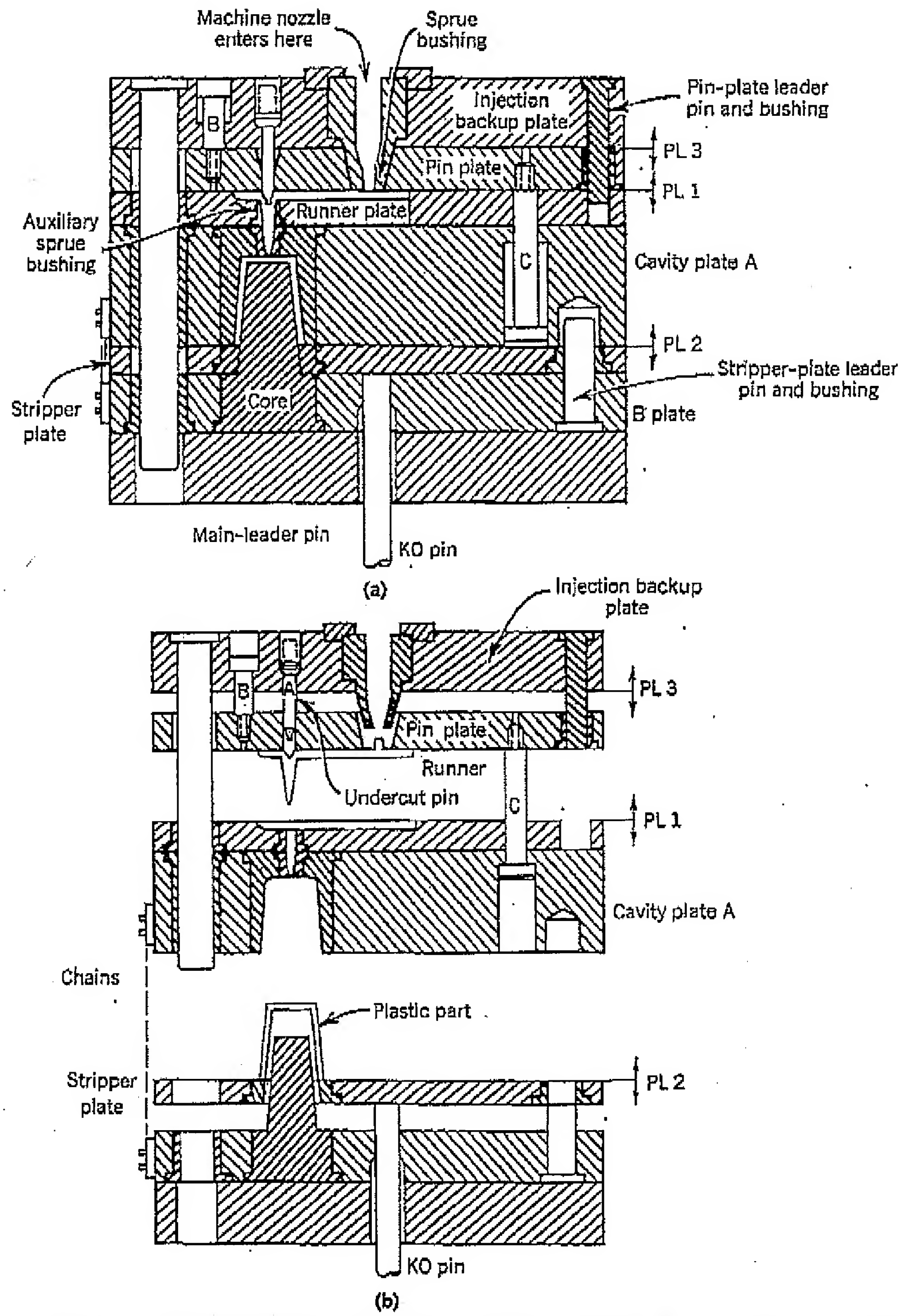


Fig. 10. Three-plate mold in (a) closed position and (b) open position. A, undercut pins; B, C, stripper bolts.

bolts, B. When moved forward (by latches, chains, stripper bolts, ejector bars, or air cylinders), the runner is stripped off the undercut pins and the plastic sprue is moved forward out of the bushing. The runner can be removed by hand, air blast, or mechanical wiper. Runner plate and *A* plate always stay on leader pins. The pins must be long enough to separate the plates far enough to remove the runner. It is good practice to support the pin plate on its own leader pins attached to the backup plate. This prevents it from binding on the main leader pins.

This type of mold performs well, provided the workmanship is of good quality and the components fully sized and adequately designed. If not, cocking and binding occur. An extra set of leader pins and bushings are sometimes required to support the *A* plate. These should not be used to line up the *A* and *B* plates. In other instances, small leader pins and bushings are inserted into *A* and *B* plates to assure lineup and compensate for wear on the long leader pins.

Hot-runner Molds. The plastic runners are reground and reused. A logical extension of the three-plate mold overcomes this and is called a hot-runner mold. It is a block of steel heated with thermostatically controlled electric cartridges which keep the plastic fluid. The material is received from the injection cylinder and forced through the hot-runner blocks into the cavities. This type of mold is more difficult to build and operate than a three-plate mold, but produces parts less expensively (8).

Insulated-runner Molds. A combination of a hot-runner mold and a three-plate mold is called an insulated-runner mold (8). The gating system is very similar to that of a three-plate mold, except that the runners are very thick, ie, at least 45 mm (1¾ in.) in diameter. There is no runner plate and the backup plate and *A* plate are held together by latches. After the material is injected, the outside of the runner freezes but insulates the center, permitting the core to remain fluid at molding temperatures and act as a hot runner. If the runner freezes during start-up, the two plates separate and the runner system is removed. The mold can be operated as soon as the runner reaches equilibrium. These molds are more difficult to start and operate than a three-plate mold.

Materials for Cavities and Cores. The principal material of construction for molds is steel, followed by beryllium copper alloy. Brass, aluminum, and steel-filled epoxy are also used.

Steel. Steel is the most common material for injection-mold sets, cavities, and cores (1). The type of steel selected depends on end use, part size, and method of fabrication. It should be free from defects, have minimal distortion during heat treatment, be easily machinable, polish well, and weld readily.

To resist the stresses of injection molding and give reasonable protection against damage during production, a minimum hardness is required. In the United States, the Rockwell C scale is used; in other countries, it is the Brinell system. If the steel is too hard, it becomes brittle. If it is too soft, it does not provide enough protection against damage and wear. Steel with a Rockwell C (Rc) of 50–55 gives good results, although it is difficult to machine even with carbides. It is easily worked by grinding and electrical or chemical removal equipment. The cavity or core is machined in the soft condition as it comes from the steel mill. Hardening is done by raising the steel above its critical temperature and quenching it in air, brine (water and salt), or oil. It is immediately annealed to the desired hardness.

Mold parts are sometimes nitrided, that is, they are subjected to ammonia gas up to 650°C for 50–90 h. Distortion is practically nil and a very hard, tough, thin case is produced.

Most large molds are made in prehardened steel Rc 28-44, which can be machined. This prevents distortion and cracking that can happen if a part is hardened after fabrication.

Beryllium Copper. Beryllium copper is an alloy of copper containing approximately 2.75% beryllium and 0.5% cobalt. It is softer than steel, and exhibits much higher thermal conductivity (9). Since the time required for cooling a plastic in the mold is a function of the rate of heat removal, a beryllium cavity should give faster cycles. If cooling is the limiting factor in the molding cycle, this is true. The costs of beryllium copper cavities and cores are about the same as that of steel, and material selection depends on the mold properties desired. Beryllium copper can be polished to a high gloss; it is not affected by water, and when flash chrome-plated, gives an excellent, durable, molding surface.

Surface Finish. The surface finish of a mold affects appearance, ejectability, and cost. It is specified by comparing it with six different finishes; this is an SPE/SPI standard which is available from SPI.

Molds are polished with abrasives, starting with coarse grits and finishing with grits as fine as 20 μm (ca 600 mesh). Stones, emery cloth, carborundum in oil, and diamond compound are used. Steels rust easily and an anticorrosive coating should be applied at room temperature. Stainless steel, electroless nickel, or chrome plating prevent water damage.

Equipment for Fabricating Cavities and Cores. Toolroom equipment is used for machining mold bases, cores, cavities, pins, blocks, and other parts. Fabrication can be assisted by electronically punched tape and CAM.

A drill press is a tool which has a stationary table above which is a rotating motor-driven shaft. The shaft contains a chuck to which the drill or other tool is attached. The drill moves up and down; it can be operated manually or automatically.

A miller is a drill press with a table that can be moved horizontally in and out plus up and down. The head tilts and its rotating shaft or spindle moves up and down. These movements can be controlled automatically or manually. A separate attachment has a stylus which traces a three-dimensional replica of the part to be cut in steel. The cutting tool moves proportionally in the same direction as the tracer. This is now called a duplicator.

A lathe has a rotating head to which the material to be cut is attached. The material rotates and the carriage containing the cutting tools moves along the length of the bed or across it. The tail stock is equipped with a chuck for drilling and reaming.

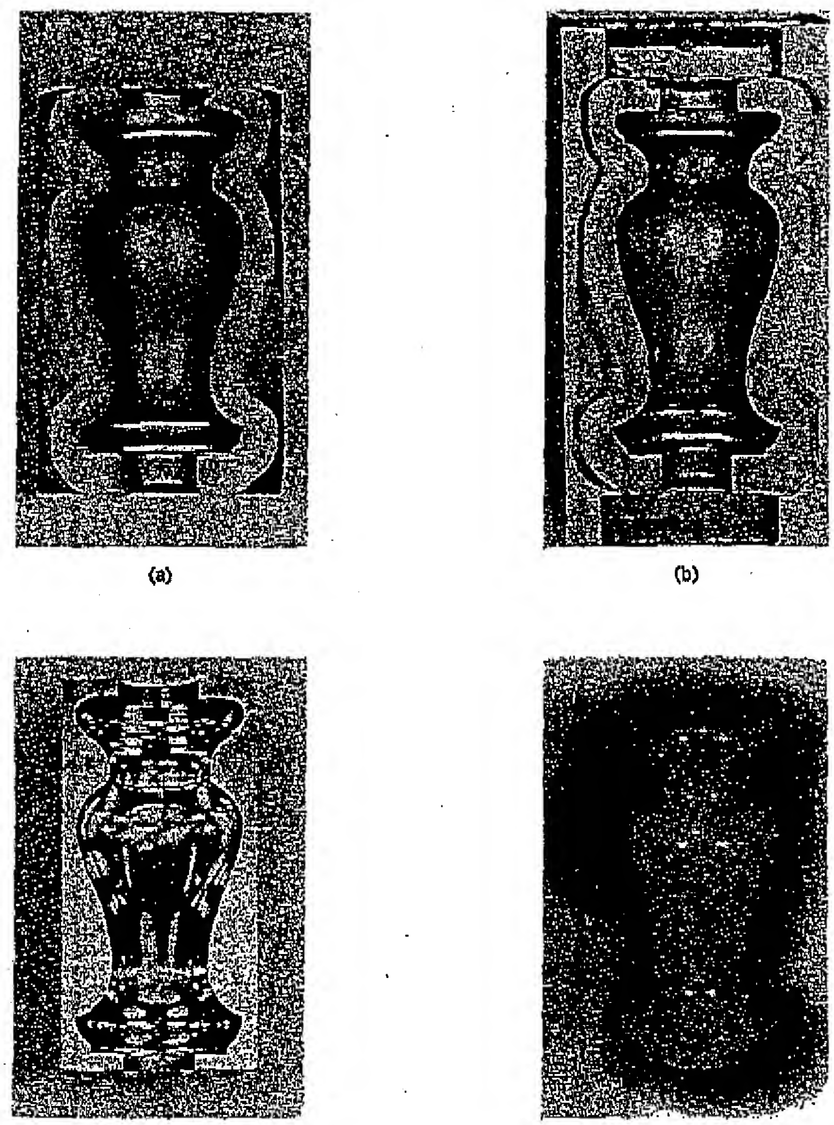
A grinder has a rotating head to which a grinding wheel is attached. The table reciprocates left and right in such a way that the circumference of the wheel performs the grinding. It can move a predetermined distance in and out with each reciprocation of the table. The height of the grinding wheel above the workpiece is accurately adjusted. The grinder is used to obtain accurate dimensions and an acceptable surface finish. It readily grinds hardened steel.

Band saws consist of two wheels around which an endless saw blade rotates. Cutoff saws have straight reciprocating blades.

Hobbing. Hobbing is a method of cold forming metal. The term is used in plastics for the high pressure cold displacement of one material by another. For

example, if a piece of plastic is left on a mold and the clamping pressures of the machine forces the plastic into the steel, the plastic is said to have hobbed itself into the mold. This term is used in moldmaking for the process that forces a hardened steel replica (hob) of the plastic part by means of high pressure into a soft iron or very mild steel block. Iron being very ductile, flows around the hob, giving an identical, but reversed impression.

Hobbing is a fast economical way to produce multiple cavities of the same size. A high polish on the hob is transferred to the cavity. Since the cavities are made of iron, they must be hardened by carburizing after they are machined to size. The hob for a molded plastic column is shown in Figure 11. The hob (a) is identical in shape with the molded parts, but smaller than the hob because the



(a) (b) (c) (d)

Fig. 11. (a) Hob; (b) hobbed cavity; (c) finished cavity; and (d) molded part. Courtesy of Robinson Plastics Corporation.

plastic shrinks on cooling (10). Figure 11(b) is the hobbed cavity and (c) is the completed carburized, polished cavity ready for insertion into the mold.

Pressure Castings. Beryllium copper cavities and cores are fabricated by pressure casting or, more accurately, hot hobbing. The hob is larger than the finished plastic part. After hobbing, the alloy shrinks as it cools just as plastic shrinks after molding. The hob is made of a good-quality, hot, working die steel that does not deform under the temperatures and pressures of casting. For one or two cavities, a different alloy of beryllium can be used for the hob.

The hob is placed in the bottom of an insulated cylindrical container. The melted beryllium copper is poured over it and forced into place by a plunger. After the alloy is cooled down, the hob is separated and can be used again. The surface finish of the cavity depends on the quality of the hob. Because the beryllium is poured on in a liquid state, delicate fins and parts can be hobbed, something not possible with cold-steel hobbing where high pressure would cause the hob to snap. The dimensions of the cavities, however, are not as accurate as those obtained from cold hobbing because of shrinkage. For most applications, this is no problem.

With an uneven parting line, hot hobbing significantly reduces costs. The parting line can be cast in such a way that a minimum of fitting is required. The costs of beryllium alloy and steel cavities are similar, and the choice is based on engineering considerations (11).

Beryllium alloy can be readily cast using gravity alone and still give excellent surface reproductions. The casting is less dense than pressure casting and may not be watertight.

Casting. Casting is readily adaptable for injection molding. Any metal can be cast, especially with the Shaw process. In this patented process, a sample or a plaster reversal of the part in plastic, wood, metal, or other material is cast against a ceramic slurry. The slurry is fired and gives a reverse ceramic reproduction with a micrograin structure containing small air gaps. The gaps act as vents and the molten metal can achieve a good reproduction of the surface. The resultant cavity is not as dense as those produced by other methods and may contain small pits. The shrinkage factors for slurry, metal, and molding must be calculated. A new slurry casting must be made for each new cavity. The major advantages of casting are its speed and cost. A cavity can be made in less than a week. The economics depend on the size and nature of the part (12).

Electroforming. Early methods of electroplating could not be used for mold cavities because the stress in the plating causes deformation. This difficulty has now been overcome. A master, sometimes called a mandrel, is an exact reverse of the cavity. On it is plated ca 3.8 mm (0.015 in.) of a nickel cobalt compound at the rate of ca 0.1 mm/8 h (0.004 in./8 h). On top of this copper is electroplated, which is harder than mold steel. The rustproof finished cavity has good dimensional stability and high thermal conductivity and is very precise within 25 μm (0.0001 in.).

Electroforming is used primarily where high accuracy is required, such as in gears and where exact reproduction is needed. Irregular parting lines can be made with a near-perfect match. Irregular shapes that would be difficult to machine can be electroformed easily. There is no distortion from hardening in the finished cavity. The plating solution can be flushed into deep crevices forming very narrow and thin slots.

Duplicating. This process is mechanical reproduction by means of cutting tools which are guided by a master, proportional in size to the desired finished parts. Duplicating is mostly used for large parts; hobbing or casting is more economical for small parts. Large automatic duplicators are powerful horizontal millers with hydraulically controlled feeds. Maximum cutting speed is obtained with feedback and electronic techniques. Mirror images are easily produced automatically and are tape-controlled. Small duplicators are often used for hobs or engraving small designs, letters, and numerals on cavities and making electrodes for spark erosion. Surface finish, however, is usually poor.

Spark Erosion. Steel is easily removed by an electrical-discharge machine (EDM). An electrode, made of carbon or copper or other conducting material, is made in the reverse shape of the part to be produced. The steel and electrode are immersed in a circulating solution that serves to flush away the eroded material and cool the workpiece. When a-c power is rectified and charged into a capacitor system, the discharge between the electrode and the cavity creates a spark which erodes the steel. The electrode is eroded about one tenth as fast as the steel. Roughing electrodes shape the cavity and a finishing electrode adjusts the size.

The process is accurate and produces good detail. It can be used on hardened steel without any distortion and for cutting thin slots. The distance between cavities can be reduced and cooling improved by eroding on one plate rather than inserting cavities. Cutting is relatively slow. The preparation of the electrodes and the operation of the equipment require good workmanship. Spark erosion is widely used for changing and correcting hardened steel.

Tolerances. A mechanical tolerance is the total permissible variation of size, form, or location. It is indicated as a unilateral tolerance in which the variation is from a given dimension in one direction only, or a bilateral tolerance where the variation is permitted in both directions. Tolerances prescribe the part limits, which should be controlled by function and appearance.

Suggested tolerances on molded parts in different plastics have been published by the Society of the Plastics Industry and material suppliers. If finer tolerances are required, the rejection rate rises significantly and costs increase accordingly.

Piece-part tolerances are different from functional tolerances required to make the mold function. These are the sole responsibility of the molder and moldmaker.

Parting Line. When a mold closes, core and cavity meet, producing an air space into which the plastic is injected. This junction appears on the molded piece as a line called the parting line. If a piece has cam or side actions, it might have several parting lines. The term parting line is usually restricted to the line that is related to the primary opening of the mold.

The selection of the parting line is influenced by the shape of the piece, method of fabrication, tapers, method of ejection, type of mold, esthetic considerations, postmolding operations, venting, wall thickness, orientation, number of cavities, and location and type of gating.

Venting. Since injection of hot plastic into the mold displaces air, vents are required. Vents are usually ground on the parting line. Their size depends on the nature of the material and the size of the cavity. Inadequate venting may burn the material or cause flash.

A typical vent is 0.05 mm (0.002 in.) deep and 2.5 cm (1 in.) wide. Extending

the vent for 1.25 cm (0.5 in.), would increase the depth to 0.7 mm (0.03 in.). Clearance between knockout pins and their holes provides venting. Special pins are sometimes inserted into the mold for venting purposes.

The gate location is affected by venting; gating is often restricted because of the inability to vent the mold completely. Rapid injection is frequently desirable, which may be slowed down by inadequate venting. The location and size of vents are still governed mainly by trial and error.

Ejection. The molded part is ejected by knockout (KO) pins, sleeves, stripper rings, stripper plates, air, or a combination of these methods. The quality of the molded piece is influenced by the method of ejection. Undercuts are pieces of mold material which obstruct ejection.

The geometry of the parts and the type of plastic material are the principal factors in selecting the knockout system. Most parts are ejected readily with a taper of 1° per side; smaller tapers are permissible if required. A high polish is not always required, but the direction of the polish is important. Draw polishing (stoning and polishing in the direction of ejection rather than at random) is used in difficult cases. With some materials, eg, olefins and nylon, fine-sand blasting may help. Normally a moderately polished surface does not present ejection problems.

The cross-sectional area of the KO pins or rings must be large enough to prevent damage by the knockout. Knockout pins penetrating the molded parts can produce serious stress in the KO area as demonstrated in birefringence studies of transparent molded parts. Large-diameter knockout pins are recommended.

A stripper-plate ejection system with stationary core pins is shown in Figure 12. The core pins are surrounded by hardened replaceable stripper bushings mounted in the stripper plates. Wear is minimized by a clearance in the lower part of the stripper bushings. The knockout bars cause the stripper plate to move

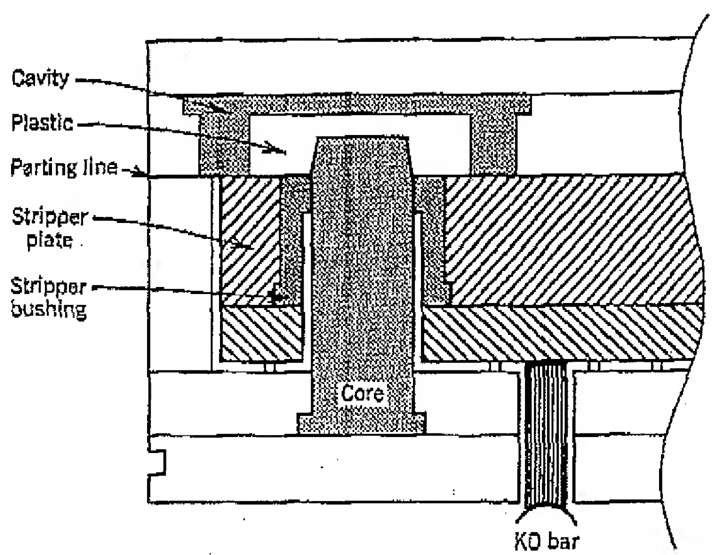


Fig. 12. Stripper-plate ejection system.

in relation to the core pin, stripping it off the core and leaving it on the plate or free to fall off. Sometimes it is necessary to eject in two stages (double knockouts).

A retractable core prevents difficulties caused by entrapped material (see Fig. 13). Material flowing in from the gate presses the metal ring, B, outward because of Hookean elasticity. After the injection pressure is released, the metal ring snaps back squeezing and entrapping the ring of plastic, A, between the metal ring, B, and the core, C. This generates huge frictional forces which are not relieved when the mold opens and the cavity is displaced.

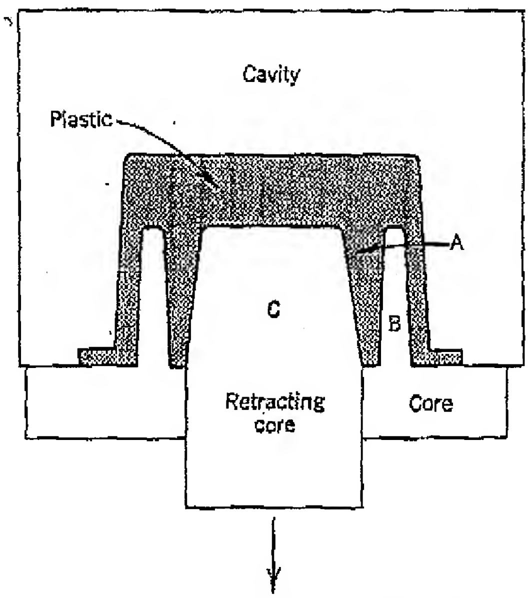


Fig. 13. Retractable core to prevent ejection difficulties caused by entrapped material. A, Ring of plastic; B, metal ring; and C, core.

Removal of the core pin before ejection allows the plastic to move and eliminates the extra friction caused by the steel-ring deflection. In practice, the core is not retracted but the core plate moves forward either by heavy springs or the knockout system. A secondary knockout system ejects the pieces.

Cam-acting molds are commonly used for injection molding. They are primarily used for molding parts with undercuts and holes, which, if left in place, would prevent ejection in the direction of the machine movement. They are also used for engineering reasons relating to ejection, venting, and gate locations.

Internal threads can be molded automatically by using a collapsible core (13). Automatic unscrewing mechanisms include racks and pinions, gears, sprockets, electric motors, and hydraulic motors. Automatic unscrewing molds are expensive to build and maintain. An alternative is mold inserts that are removed with the piece and unscrewed on the bench; extra inserts save machine time. Other techniques include using threaded mold inserts, adding metal inserts in a postmolding operation, or tapping the hole in the plastic.

Runners. The runner connects sprue and gate. It should be large enough to allow rapid filling and minimum temperature and pressure loss, but not so

large as to prevent or slow down ejection. The runner is usually reground and reused. Regrinding, however, is expensive; it wastes material and energy and is a source of contamination.

For a given cross-section, a full round runner permits the greatest flow. It has the highest ratio of cross-sectional area to circumference, minimizing the cooling effect. The material feeds from the center which is the hottest. A trapezoidal shape is recommended if a runner is on one side only. Half-round and rectangular runners should not be used. The runner should be polished and free of sharp corners to reduce flow turbulence. The flow rate into the cavity should be controlled by the gate, not by the runner.

Gates. The gate is the connection between the runner and the molded part. It must permit enough material to enter and fill the cavity, plus material lost through shrinkage.

Gates can be classified as large or restricted (pin-pointed). Restricted gates are circular in cross-section and for most materials do not exceed 15 mm (0.060 in.) in dia. For more viscous materials, restricted gates may have diameters of 3 mm (0.115 in.). A large gate, which is usually square or rectangular, is 6.3 mm (¼ in.) wide and 4.7 mm (³⁄₁₆ in.) high. Large gates are used for molding heavy sections and where the restricted gates create surface blemishes.

The restricted gate is successful because the viscosity of the plastic is sensitive to the shear rate, becoming less viscous with higher speed. As the material is forced through the small opening, its velocity increases. The velocity is directly related to the shear rate. Once the gate is opened to the extent where it loses this shear rate viscosity improvement, a much larger opening is required to obtain acceptable flow.

Gates are also described by such terms as edge-gated, back-gated, submarine-gated, tab-gated, and nozzle-gated. Various types of gates are shown in Figure 14. A sprue gate feeds directly into the piece from the nozzle of the machine or runner. Flow is short and direct and pressure loss is minimal. Its disadvantages include the lack of a cold slug, the possibility of sinking around the gate, high stress concentration around the gate, and the need for gate removal. Most single-cavity molds of any size are gated this way.

Edge gating is the most common; it can be large or restricted. A spread-out edge gate is called a fan gate. An extended gate connected by a thin section of plastic is called a flash gate. Sometimes it is necessary to have the gate impinge upon a wall. This distributes the material more evenly and improves surface conditions. If walls are not available, a rectangular tab is milled into the piece and the gate is attached there. This is called a tab gate. Blemishes are eliminated when the tab gate is removed.

In gating into hollow tubes, flow consideration can require an even injection-flow pattern, and a single gate is not sufficient. Several gates give several flow lines down the side of the piece, which may be objectionable. If a diaphragm gate is used, the inside of the hole is filled with plastic directly from the sprue and acts as a gate. The gate must be machined out later. A ring gate gives the same result from the outside.

A submarine gate penetrates through the steel of the cavity. When the mold opens, the part sticks to the core and shears the piece at the gate. A properly placed knockout pin, taking advantage of the flexibility of the plastic, ejects the runner. This type of gate is used in automatic molds.

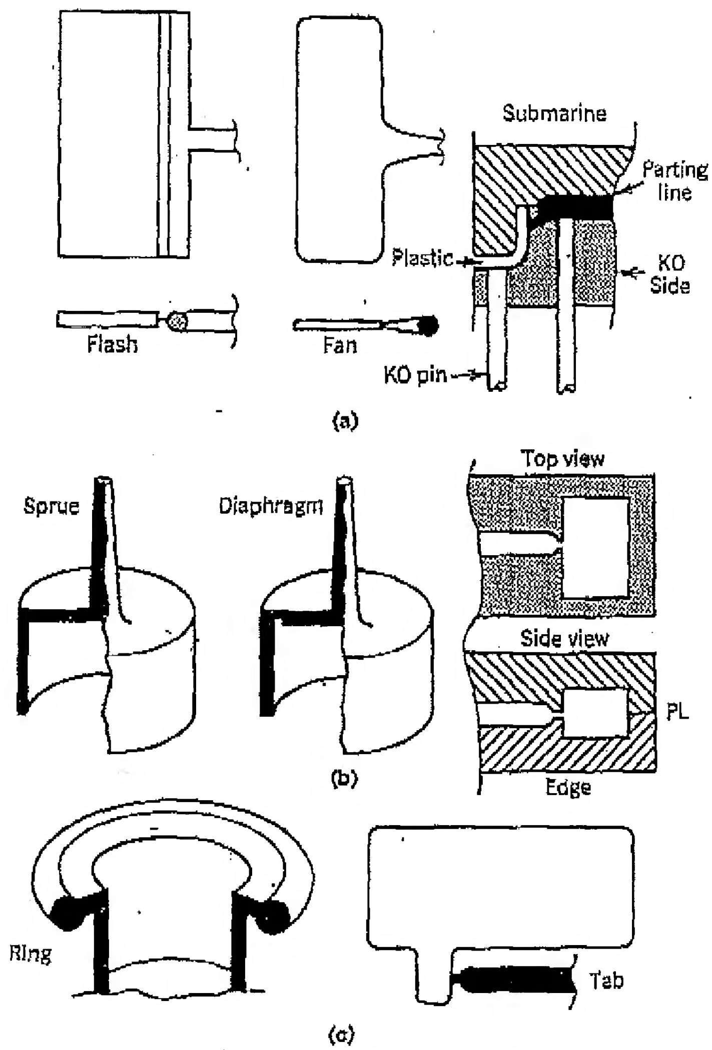


Fig. 14. Various gating designs. (a) Submarine gate; (b) edge gate; (c) tab gate. Courtesy of Robinson Plastics Corporation.

Restricted gates give better mixing (Reynolds effect). A good variegated pattern can only be obtained with a large gate.

In multiple-cavity molds, the gate size must be adjusted in such a way that all the cavities are filled at the same time. If not, severe molding and dimensional problems may develop. Such parts are more subject to long-term failure.

Temperature Control. For consistent molding, strict temperature control is required (14). Refrigerated water and hot water to 93°C is required at each machine. The optimum temperature is determined by trial and error. Different parts of the mold are often maintained at different temperatures. Cold water is distributed from one central unit or from small portable chillers. Electrical-heating units are employed to control the temperature of the mold. They include bands, cartridges, and strip heaters controlled by pyrometers.

The main purpose of temperature control is to remove heat from the plastic part at a controlled rate. The amount of heat removed depends on the material,

the metal in which it is contained, the size of the cooling channels and their locations, and the rate of flow of the heat-exchange fluid. Air is an effective insulator and it is desirable to locate the cooling channels in the cavity and the core. The minimum cooling channels should be "¼" taper pipe, although ⅜ taper pipe is preferred.

Mold temperature control is so important that molds are built at a considerable extra cost for greater cooling.

Automation. An automatic molding machine must be capable of consistent repetitive action including clearing itself automatically. In a runnerless mold, parts have to be ejected. In a conventional mold, the runners and the parts have to be ejected and separated. A wiper mechanism or an air blast assists in the removal of the pieces. All automatic machines must have a low-pressure closing system which prevents the machine from closing under full pressure if there is any obstruction between the dies. The machine shuts off, and an alarm is sounded.

Automatic molding produces a superior part faster than manual machines. An operator can feed and attend several machines at the same time and pack and perform secondary operations.

Automation is expensive. It requires high quality machinery, controls, and molds, as well as trained personnel and managerial skill. It can be a highly satisfactory and economical operation.

High Quality Parts. A well-designed and built mold provides high quality parts. Quality-control specifications are used as a guide. Different samples are molded under different conditions and a record is kept; each sample is tested. This process is repeated until a set of conditions is found that consistently provides a high quality part.

There is no practical nondestructive way to determine the quality of a molded part. Molding conditions provide the best control; computerized machines with feedback are most economical. They reproduce the operating conditions with a high degree of accuracy and eliminate manual inconsistencies. They reproduce identical injection-rate profiles which are needed to maintain identical viscosity from shot to shot.

Molecular Aspects of Injection Molding and Physical Properties of Molded Parts

The polymeric materials used in the molding process may be completely amorphous, or partly amorphous and partly crystalline. Varying amounts of thermal and frictional or shear energy are required to provide the plastic flow conditions necessary for good moldings. The viscosity of the melt must be sufficiently low to allow the injection pressure to force the plastic into the cold mold.

As the temperature increases, the energy absorbed by the polymer chains causes vibrational, rotational, and translational or segmental motion of the polymer molecules. This essentially Brownian motion results in a random molecular arrangement.

If a unidirectional force is applied to a polymer at rest (in a random configuration) above its glass-transition temperature, it moves away from the force. If the force is applied gradually in such a way that the Brownian movement can

overcome the orienting forces caused by the flow, the mass of the polymer moves with a rate proportional to the applied stress. This is termed Newtonian flow (see also RHEOLOGY).

As the molecules move more rapidly under the influence of higher pressures in the injection process, the chains untangle and tend to orient in the direction of flow. Chains move so rapidly that there is not sufficient time for the Brownian motion to have an appreciable effect. In addition, the molecules tend to slide over each other more easily since they are oriented in one direction and are less entangled and farther apart. Therefore the increased shear rate is no longer proportional to the shear stress. This is non-Newtonian flow. This is characteristic of plastic or polymer flow, ie, shear rate is no longer linearly proportional to shear stress. Therefore it can be assumed that injection molding or extrusion causes orientation of the molecules as they are transported through the sprue runner and gate.

As the flow rate increases, it reaches the final stage with maximum molecular orientation, and there is no further untangling. Increase in the shearing stress increases the shearing rate and the material again acts as a Newtonian fluid.

Orientation. As the material enters the cold mold, it freezes. Regardless of any orientation caused by the gate, the turbulence in the flow is enough to randomize the outside molecular layer. This outside frozen layer is therefore relatively unoriented. Part of the polymer molecule adheres to the wall. The material flow pulls the remainder of the molecules in the direction of flow. These layers as would be expected are the most highly directional or oriented and the most highly shear-stressed. Nearer the center, the molecules are less oriented. The closer the polymer is to the wall, the quicker it freezes (see also ORIENTATION; ORIENTATION PROCESS). Because the outer layers provide thermal insulation, the inner portion retains heat longer, allowing more time for Brownian movement and disorientation.

If a clear injection-molded part is placed between two polarizing light filters, one of which is rotated, a characteristic series of colored bands appear primarily related to orientation stress in the part. This phenomenon is called birefringence (see OPTICAL PROPERTIES, BIREFRINGENCE).

The degree of birefringence (in the molded part) vs the distance from the mold wall is shown in Figure 15. The dashed line indicates the initial condition and the solid line, the final condition when the part cools. The reduction in orientation is caused by Brownian movement. Measurements of various moldings were taken with the aid of a polarizing microscope (15,16). Peak orientation is between 0.63 and 0.76 mm (0.025 and 0.030 in.) from one side of a 2.54-mm (0.100-in.) thick slab. The two peaks are not identical in each specimen, reflecting the difference in temperature of each side of the mold.

Milling off about one-third of either side produces a part with molecules randomly placed on one side and highly oriented on the other. If the specimen is heated above its T_g, the oriented molecules should assume a more random structure causing a shrinkage of the oriented portion. The specimen should act like a bimetallic unit and bend in the direction of the oriented layer (Fig. 16) (17).

Orientation has, of course, an effect on physical properties of the molded

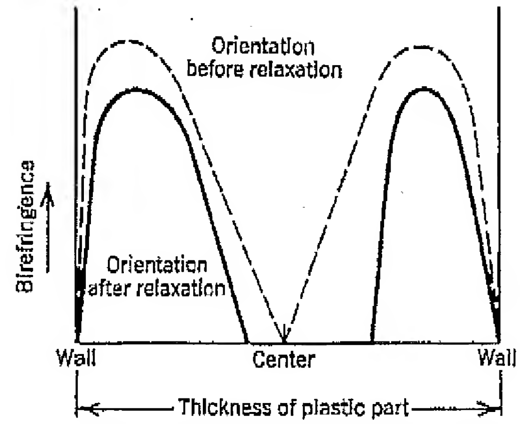


Fig. 15. Birefringence vs distance from wall (15).

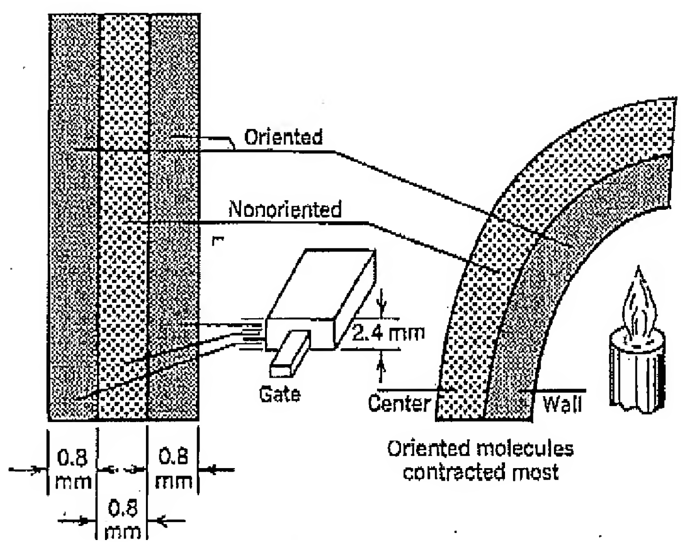


Fig. 16. Effect of orientation resulting in nonuniform shrinkage (17).

part. For example, a brittle polystyrene sheet has a tensile strength of 41–48 MPa (6000–7000 psi). It is heated slightly above T_g and stretched. While it is under tension it is chilled to retain its orientation. The tensile strength is then 62–82 MPa (9,000–12,000 psi), depending on the elongation and processing temperature; the brittleness disappears. If this material is allowed to cool slowly, its orientation disappears and the properties are similar to those of the original sheet (18).

The effect of orientation (measured by birefringence) upon tensile strength, elongation at failure, and notched Izod impact test is shown in Figure 17.

The polymer is held together by two forces: C—C covalent linkages have a dissociation energy of 347.4 kJ/mol (83 kcal/mol); van der Waals forces are approximately 12.5–20.9 kJ/mol (3–5 kcal/mol) and decrease exponentially as the 6th power of distance. Therefore, tensile strength increases in the oriented flow direction because there are more C—C linkages in that direction than perpen-

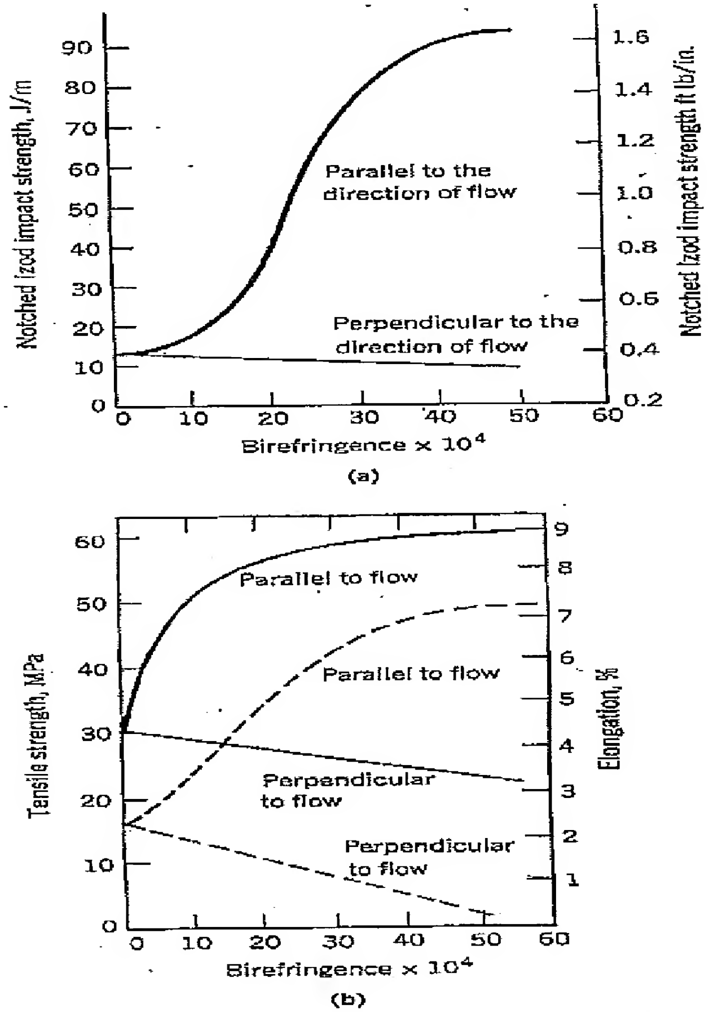


Fig. 17. Effect of orientation on (a) impact strength. To convert J/m to ftlb/in., divide by 53.38. (b) Tensile strength and % elongation to failure of polystyrene (16). To convert MPa to psi, multiply by 145.

dicular to flow. These linkages are much stronger than the van der Waals forces, which are the major forces holding the polymer together perpendicular to flow. This also affects the percent elongation at failure and the notched Izod impact.

Effect of Molding Conditions. Molding conditions, part thickness, and gate size affect orientation. The net orientation is the difference between the orien-

tation caused by flow and that lost by relaxation. Usually a higher stock or material temperature produces less orientation because hotter material relaxes more. However, in thin section the hotter material may permit faster flow. With large gates, hotter material keeps the gate open longer increasing the flow time and hence the birefringence.

The higher the mold temperature, the more time for relaxation and the lower the orientation. Increasing cavity thickness has a dramatic effect on decreasing overall orientation. Because of the low thermal conductivity of plastic, the interior remains hotter longer, increasing relaxation.

Prolonging the forward motion of the ram increases orientation by extending flow time. This effect stops when the gate is sealed off. Higher injection pressures increase orientation by inhibiting Brownian movement. The larger the gate, the longer the seal-off time.

Some physical properties vary depending on the flow direction, as evidenced by orientation. More shrinkage can be expected in the direction of flow because the C—C linkages are elastic and the van der Waals forces are not.

The effect of different shrinkage parallel and perpendicular to flow is considerable in injection molding. An example is the molding of a center-gated 10-cm (4-in.) dia 1.5-mm (0.060-in.) thick polypropylene disk (Fig. 18). A segment encompassing a 60° angle has a 50.8-mm (2-in.) radius on each side of the equilateral triangle. When the hot material flows in, the polystyrene typically shrinks 0.5 mm/mm (0.020 in./in.) in the direction of flow and 0.3 mm/mm (0.012 in./in.) perpendicular to the flow. When the material cools, the radius of the disk is 49.8 mm (1.960 in.) and the chord is 50.2 mm (1.976 in.).

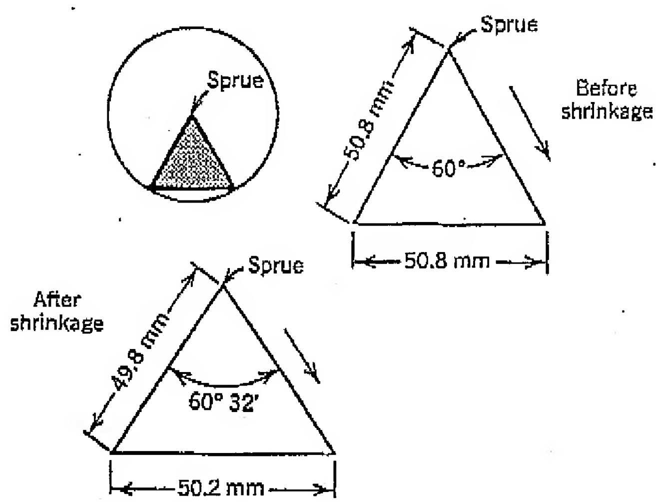


Fig. 18. Warping of center-gated polypropylene part caused by different shrinkage parallel and perpendicular to flow. Shrinkage: direction of flow 0.5 mm/mm (0.020 in./in.) perpendicular to flow 0.3 mm/mm (0.012 in./in.).

The new angle is 60° 32′. For the complete 360° circle, the increase is 3.2°. Unless the material is rigid enough to overcome this stress, the extra 3.2° of material will cause a warp. A warp-free part cannot be produced in a thin-walled cover.

If a rectangular tray of the same material is molded (Fig. 19), a center gate (a) gives a radially distorted tray unless the walls are heavy enough to overcome the stress. If gated as in (b) a severe radial twist would occur. If the part is edge-gated at one end (c), it would be warp-free, but the material would flow around the rim on the parting line and trap air, giving burns or poor welds. The best way to gate the piece would be to place two gates at one end (d). This provides maximum linear flow without air entrapment and produces a warp-free part.

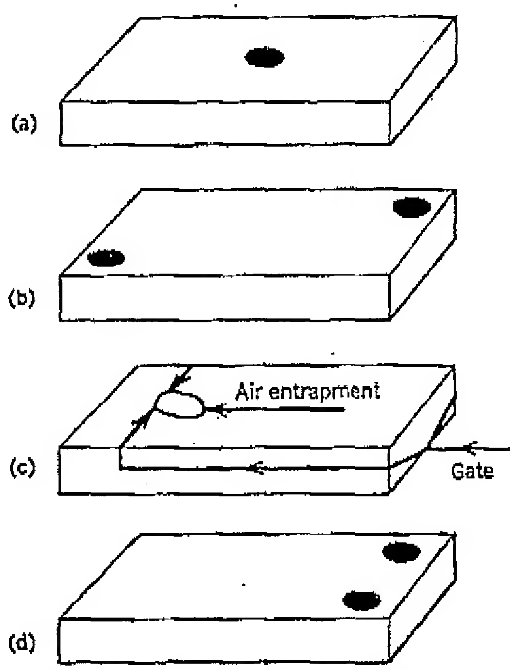


Fig. 19. Effect of gate location on polyethylene tray. (a) Center gate; (b) diagonal gate; (c) edge gate; (d) end gate.

As the polymer cools, extra material is forced in by the injection ram to minimize thermal shrinkage as the part cools. If too much material is forced in, it compresses the carbon–carbon linkages and overstresses the part causing failure particularly at the gate.

The main parameter is the ram forward time. Using an accelerated aging test, a center-gated polyethylene tumbler with a ram-forward time of 10 s had no failures the first day and 7% 14 days later. Increasing the ram-forward time to 25 s gave a 1-day failure of 70% and a 14-day rate of 88%. Injection pressure and gate size also affect packing. Although packing is concentrated at the gate, it can extend throughout the parts causing adhesion to the mold, deflecting the mold and possibly distorting the core and cavity. Obviously, the amount of feed and the temperature affect the amount of plastic that flows into a cavity and hence the packing.

All materials shrink when they cool, crystalline materials more so than amorphous materials. The degree of crystallization depends on the quenching rate or temperature drop towards the mold temperature. Thus, temperature is a critical variable in influencing the properties of the finished part. Cool molds

tend to freeze in the amorphous arrangement of the melt with less crystallinity. On the other hand, warmer molds permit the polymer to cool more slowly and thus permit more crystallization. The increased crystallinity results in greater shrinkage, higher tensile strength, lower elongation, and greater hardness.

A number of complex and opposing forces come into play when a part is molded. The hot material is injected into the cavity where it shrinks as it cools. The material is compressed by the injection pressure, permitting more material to flow into the given volume to compensate for the shrinkage. The part cools during the injection process, continually reducing its volume. The amount of additional material forced in depends on the gate size, injection rate, temperature conditions, ram-forward time, and pressure. Consequently, it is difficult to maintain really fine tolerances for injection-molded parts. The goal of proper injection molding is to balance the machine and mold conditions so that acceptable parts are produced.

Health and Safety Factors

Molding machines are hazardous; some have caused fatalities and severe injuries. The safety gate should be large enough and high enough to prevent body contact with the platen area when the platens are closing. On smaller machines a cover is essential. Both front and rear gates should be mechanically, electrically, and hydraulically interlocked to prevent the operation of the machine if open.

At no time should repairs be made requiring entry between the platens with the motor running. Moving parts such as toggles and cams should be guarded. The ends of knockout plates should be protected with clear plastic. The use of robots requires extensive guarding to prevent serious injury, particularly to the eyes and head.

The heating cylinder should be covered to prevent direct contact with the heating bands and the electrical terminals. The nozzle end of the cylinder is guarded to prevent burning by hot or exploding material during purging. Experts and agencies should be consulted for detailed safety instructions; OSHA requirements must be observed.

Summary

Advantages of Injection Molding:

1. Parts can be produced at high production rates.
2. Large-volume production is possible.
3. Relatively low labor cost per unit is obtainable.
4. The process is highly susceptible to automation.
5. Parts require little or no finishing.
6. Many different surfaces, colors, and finishes are available.
7. Good decoration is possible.
8. For many shapes, this process is the most economical way to fabricate.
9. Same item can be molded in different materials without changing the machine or mold.

10. Close-dimensional tolerances can be maintained.
11. Parts can be molded with metallic and nonmetallic inserts.
12. Parts can be molded in a combination of plastic and fillers such as glass, asbestos, talc, and carbon.
13. Aside from die casting, it is the only commercial process that can reuse its scrap immediately (regrind and remold at the machine).
14. Compared to other materials (glass, aluminum, etc), the amount of energy needed for manufacture is extremely low. From an energy point of view, the product can be reground after use and remolded or burned, both of which further reduce its energy cost.
15. The inherent properties of the material give many advantages, eg, high strength–weight ratios, corrosion resistance, strength and clarity.

Disadvantages and Problems with Injection Molding:

1. The plastic industry has very low profit margins.
2. Three-shift operations are often necessary to compete.
3. Mold costs are high.
4. Molding machinery and auxilary equipment costs are high.
5. Process control may be poor.
6. Machinery is not consistent in operation, and controls do not directly measure what is supposed to be controlled.
7. The possibility of poor workmanship is often present.
8. Quality is often difficult to determine immediately.
9. Lack of knowledge concerning the fundamentals of the process.
10. Lack of knowledge about the long-term properties of the materials.
11. Plastic cannot be made so that each pellet is the same. One must deal with averages of molecular weights and molecular configurations which vary not only from pellet to pellet but on a larger scale from batch to batch. This causes an unsteady and varying operational state. This contrasts with low molecular-weight chemicals, such as salt, sucrose, naphthalene, etc, which can be manufactured identically in structure and properties.
12. To derive quantitative equations for flow and other properties needed in injection molding, one must know viscosity, temperature, and pressure. In a mold they are continually changing and not measurable. The assumptions made may lead at best to some very questionable results when applied in practice. Experience and qualitative calculations have yielded far superior results.

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INK. See PRINTING-INK VEHICLES.

IN-MOLD PLATING. See METALLIZING.

INORGANIC FIBERS. See Supplement.

INORGANIC POLYMERS

This article is confined to descriptions of homoelement, inorganic polymeric compositions. Coverage of other inorganic polymers may be found under the titles COORDINATION POLYMERS, ORGANOMETALLIC POLYMERS, PHOSPHORUS-CONTAINING POLYMERS, POLYPHOSPHAZENES, POLYSILANES AND POLYCARBOSILANES, POLYSULFIDE POLYMERS, PRECERAMIC POLYMERS, SILICAS AND SILICATES, SILICONES, and SULFUR-CONTAINING POLYMERS.

If the term polymer refers to a structure capable of infinite extension, elements known to form homoelement polymers are restricted to the main-group elements of the carbon, nitrogen, and oxygen families (groups 14, 15, and 16) and mercury. Boron, particularly when associated with highly electronegative substituents, may some day be added to this group as suggested by the presence of cluster species of general composition $(BX)_n$, eg, $(BCl)_4$, tetrahedral, and $(BCl)_8$, square antiprismatic (1). In the present context, polyiodide ions, particularly in the form of infinitely extended arrays, are not considered homoelement polymers, but they do offer some interest in the development of two-dimensional, conductive materials (2). Most of the elements of these main-group families, in at least one allotropic form, exist in high molecular weight forms but are not considered polymers (3).

Related to the structures of elemental forms are Zintl-ion phases (4), which may be broadly defined as ions of about 4–20 atoms of the heavier group-14, -15, or -16 elements, usually forming cage and cluster structures. The anionic forms are often formed by reduction of the element by an active metal, such as